

The Perturbed Carbon Cycle

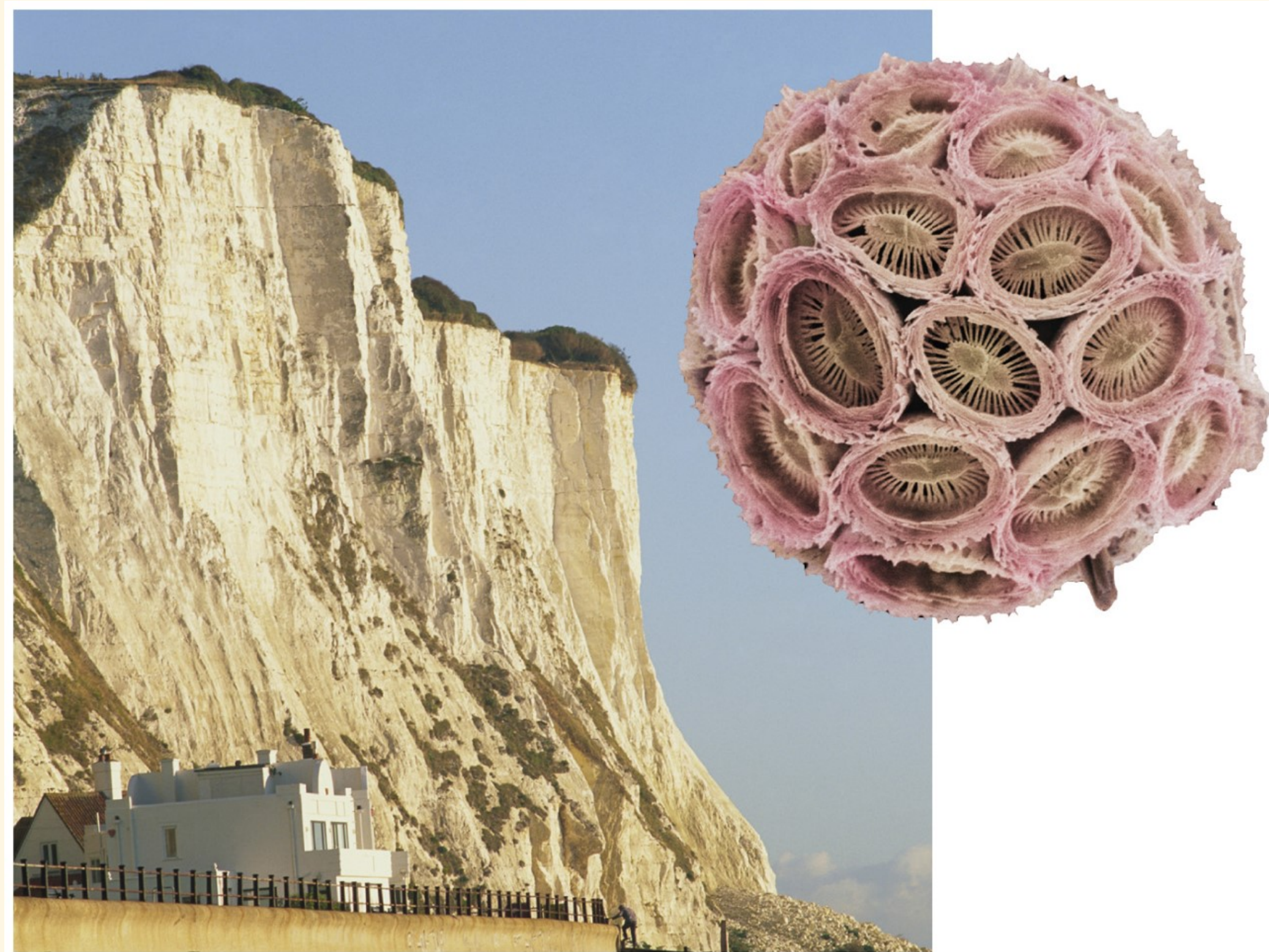
EES 3310/5310

Global Climate Change

Jonathan Gilligan

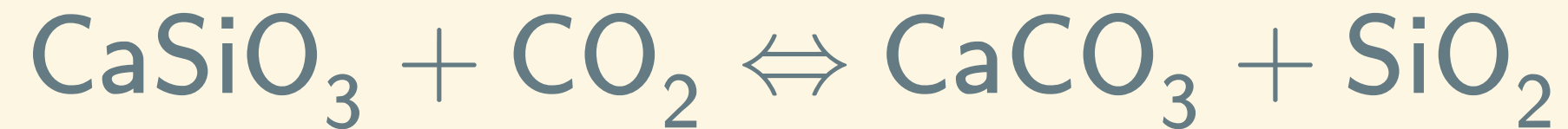
Class #12: Friday, February 19 2021

From atmosphere to rocks



From atmosphere to rocks

- Carbonate vs. Silicate minerals
- Urey Reaction:



- \Rightarrow : weathering (reactions near surface)
- \Leftarrow metamorphism (high temp./pressure deep beneath surface)
- Silicate minerals originate at high temperature (igneous)
- Carbonate minerals originate at low temperature (sedimentary)

Connection to Climate

- Rain falls on silicate minerals
 - CO_2 dissolves into rainwater
 - Dissolved CO_2 makes rainwater is acidic
- Acidic water dissolves silicate minerals
 - Dissolved ions (Ca^{+2} , SiO_3^{-2} , etc.)
- In oceans, plankton convert dissolved CO_2 & ions to calcite (calcium carbonate)
- Calcite ends up as limestone on sea floor
- **Bottom line:**
 - Weathering silicate minerals transforms atmospheric CO_2 to rocks on sea floor.

Weathering as Thermostat

CO₂ is balance of volcanic outgassing
and chemical weathering

- **Temperature rises:**
 - More rain, faster chemical reactions
 - Faster weathering
 - Atmospheric CO₂ falls
 - Temperature falls
- **Temperature falls**
 - Less rain, slower chemical reactions
 - Slower weathering
 - Atmospheric CO₂ rises
 - Temperature rises
- Net effect:
 - Keeps temperature stable near some “set point”
 - Set-point is determined by geology

Temperature of Earth

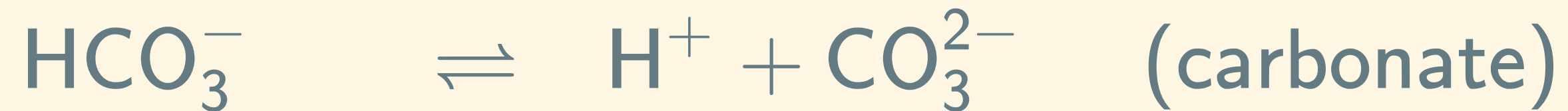
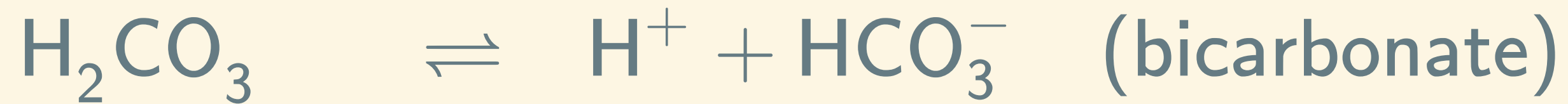
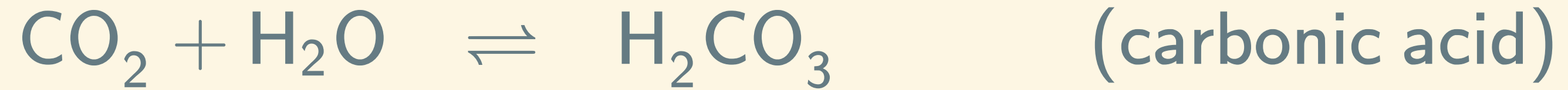
- As long as outgassing is constant, weathering acts as thermostat.
- Earth's temperature has been remarkably stable over time.
- Change of volcanic outgassing changes "setting" of thermostat.

Temperature of Mars and Venus

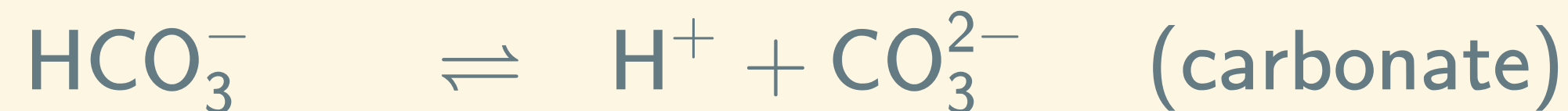
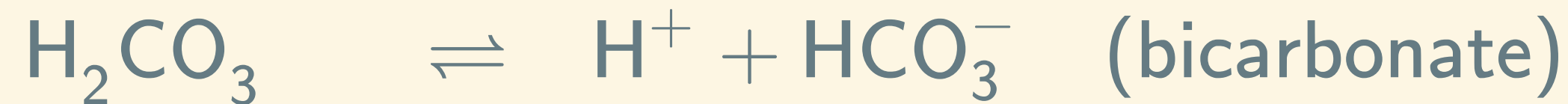
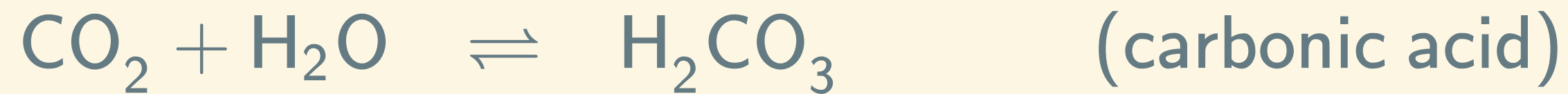
- Mars used to be warm.
 - Now it is frozen.
 - Why?
 - Volcanic outgassing stopped.
 - All CO₂ converted to rocks.
 - No new CO₂ from volcanoes.
- Venus is scorching hot
 - Why?
 - Runaway greenhouse:
 - All water evaporated
 - Chemical weathering stopped
 - Volcanic outgassing/metamorphism converted all carbonate minerals to CO₂ gas.

Carbon Chemistry

Carbon Chemistry



Natural state of ocean

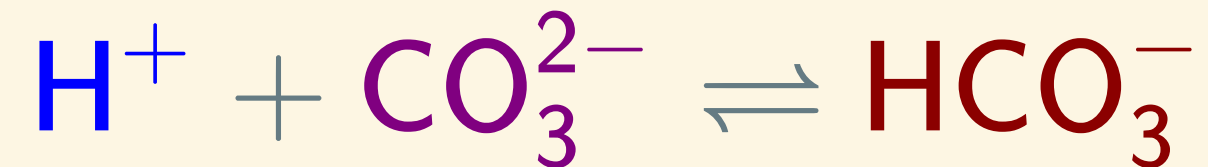
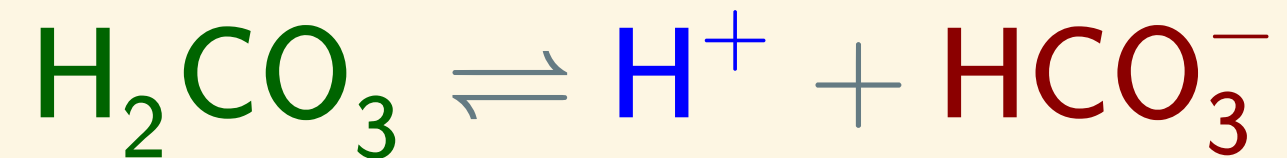


- Typical concentrations:
 - pH ~ 8 :
 - $\text{H}^+ \sim 10^{-8}$ molar = 10^{-5} moles/meter³
 - Various forms of carbon: 2 moles/meter³
 - 88% HCO_3^- ions
 - 11% CO_3^{2-} ions
 - 1% CO_2 and H_2CO_3 .
 - Don't fret about detailed numbers
- **Why is it important that there is:**
 - **200,000 times more HCO_3^- than H^+ ?**
 - **10 times more CO_3^{2-} than CO_2 ?**

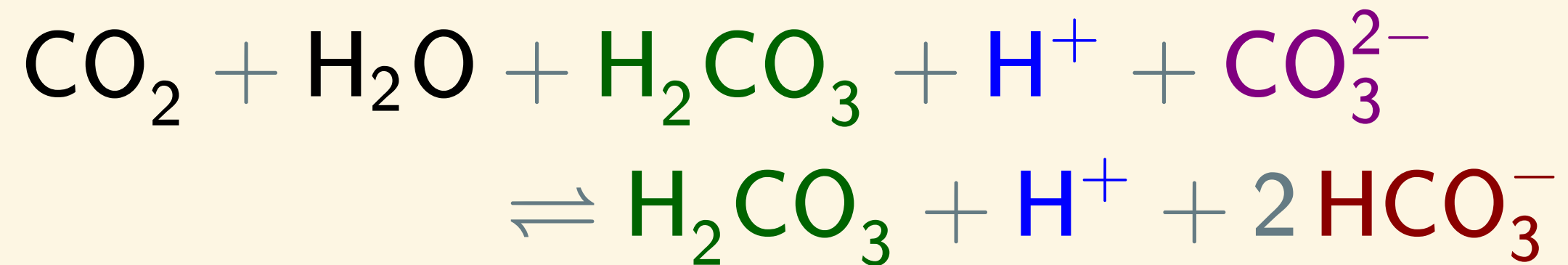
Simple treatment:

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Add the three reactions

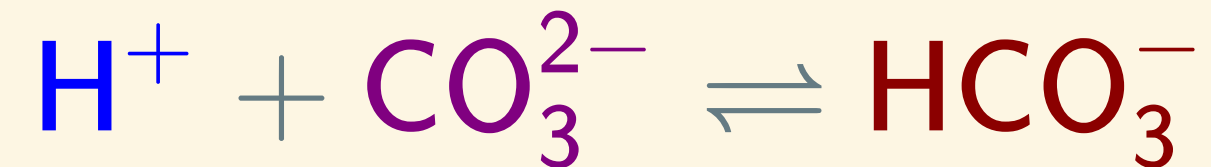
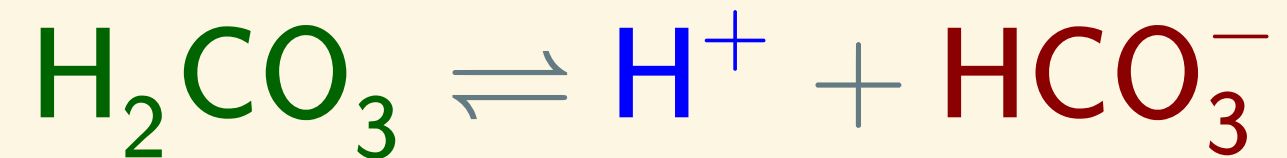


to get

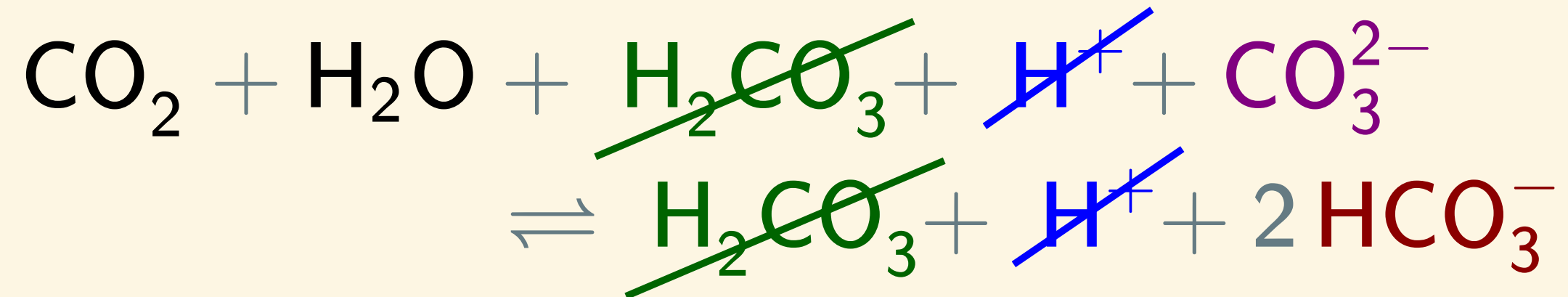


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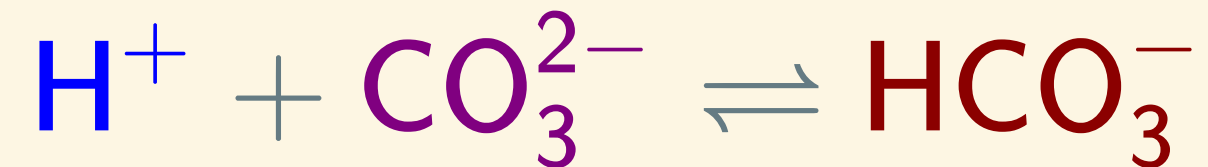
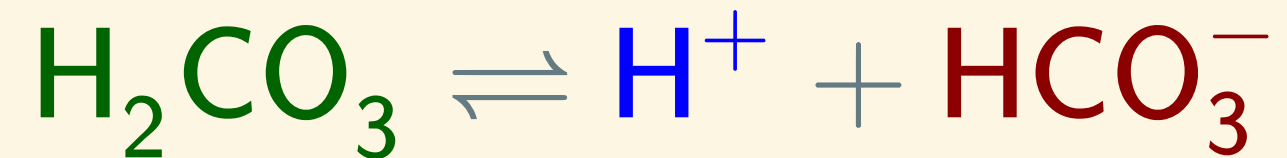
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(Cancel common terms on both sides)

Simple treatment:

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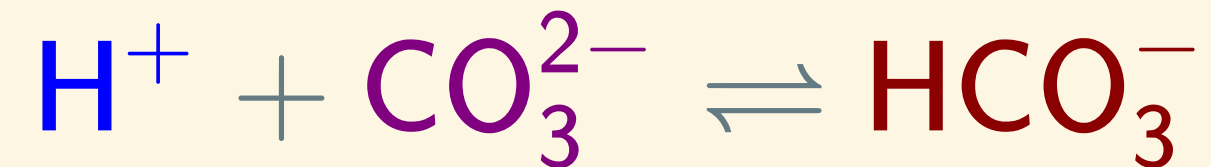
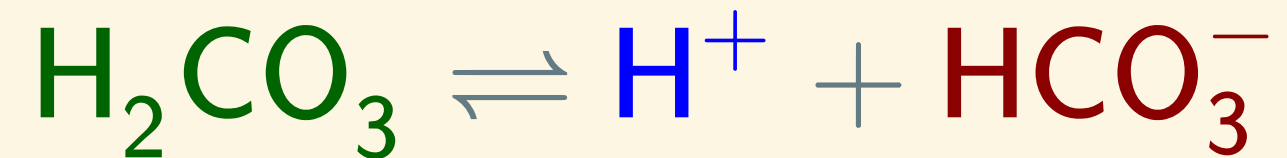
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(Cancel common terms on both sides)

Simple treatment:

Add the three reactions



to get



Now H^+ doesn't matter.

Le Chatelier's Principle:

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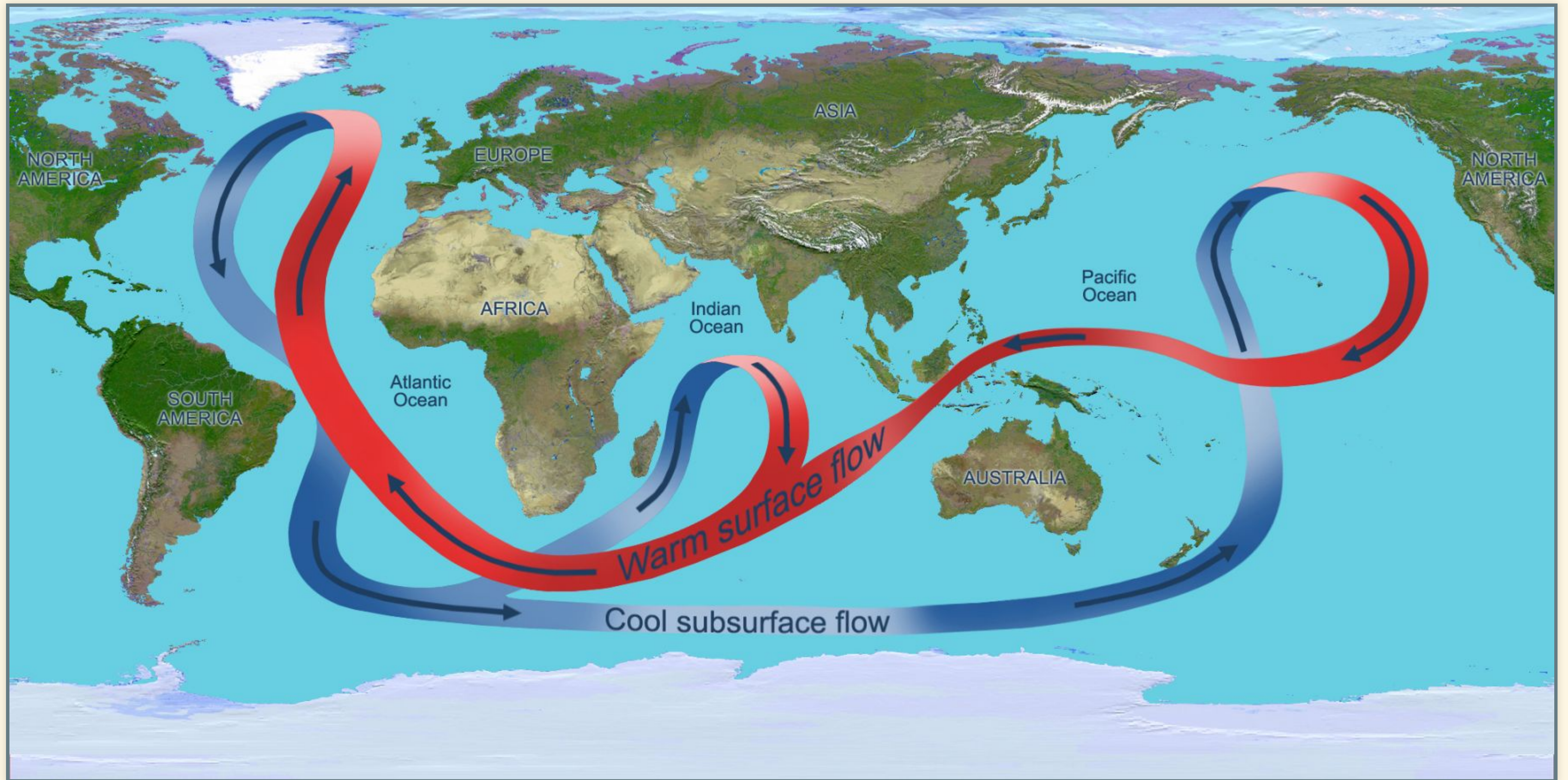
- Add more CO_2 ... What happens?
 - Le Chatelier's principle:
 - Consume excess CO_2 by running reaction to right
- Why is this important?
 - Carbonate buffering means ocean can hold 10 times more CO_2 .
- But more dissolved CO_2 means less CO_3^{2-} .
 - Why is decreased CO_3^{2-} important?
 - Without CO_3^{2-} , ocean can't absorb more CO_2 .

Anthropogenic CO₂

- **Sources:** ~11.5 GTC/year
 - 9.6 GTC from fossil fuels
 - 1.5 GTC from deforestation
 - 0.4 GTC from cement production
- **Sinks:** ~6.1 GTC/year
 - ~2.6 GTC into oceans (dissolving)
 - ~3.5 GTC into land (plants)
- **Remaining ~5.4 GTC/year stays in atmosphere.**
- Scale: 1 GTC = 1 billion metric tons carbon \approx 2ppm.
 - Numbers have changed since the textbook was published.
 - These are the latest.

Global conveyor belt

Global conveyor belt



Ocean Acidification

- More dissolved CO_2 means less CO_3^{2-}
- Surface oceans saturate: can't absorb more CO_2 .
 - Thermocline means slow mixing with deep oceans.
 - CO_2 absorption limited by conveyor bringing fresh carbonate from deep oceans.
 - Conveyor is slow (many centuries)
 - Warming oceans may slow conveyor
- **Decreasing carbonate = acidifying oceans**
 - CaCO_3 = bone, shells, teeth, etc.

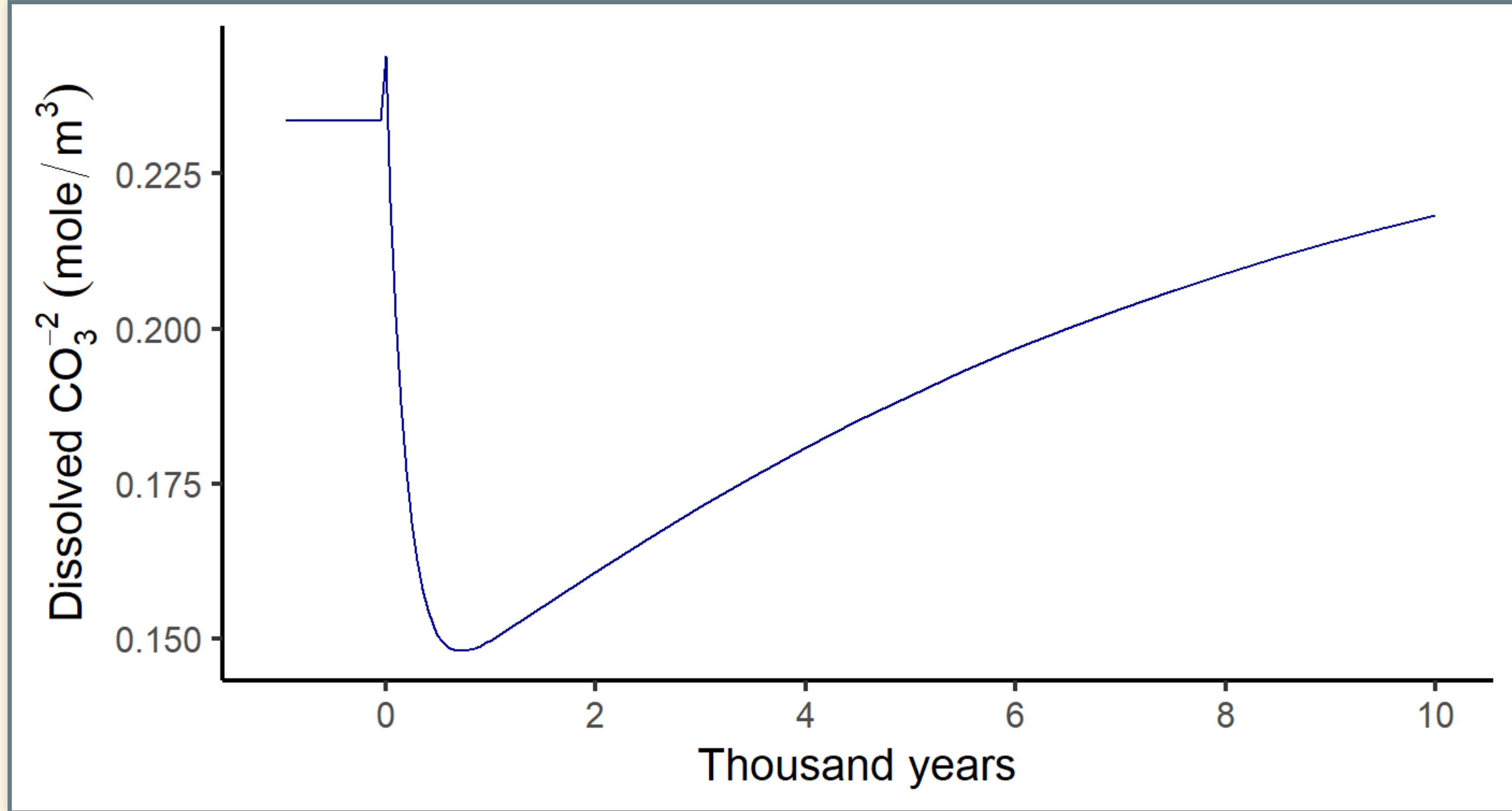


- Less CO_3^{2-} means the reaction moves to right:
 - Shells and coral dissolve
 - Damage or kill corals, shellfish, plankton, etc.

Ocean Acidification

- More dissolved CO_2 means less CO_3^{2-}
- Surface oceans saturate: can't absorb more CO_2 .
 - Thermocline means slow mixing with deep oceans.
 - CO_2 absorption limited by conveyor bringing fresh carbonate from deep oceans.
 - Conveyor is slow (many centuries)
 - Warming oceans may slow conveyor
- **Deep ocean saturation:**
 - Deep oceans run out of carbonates (centuries)
 - Only source of new carbonate is dissolving limestone on sea floor
 - Thousands of years

Carbonate after a big CO₂ release



GEOCARB model

GEOCARB model

- <http://climatemodels.uchicago.edu/geocarb>
or
<https://climatemodels.ees3310.jgilligan.org/geocarb>
- “Spin-up” establishes equilibrium
- Change at year zero
- Simulation shows how earth system responds to change over a million years
- Look at different time scales ...
- Look at different variables ...
 - [WeatS](#) = weathering of silicate minerals
 - [WeatC](#) = weathering of carbonate minerals
 - [BurC](#) = burial of carbon as limestone
 - [TCO2](#) = total dissolved carbon dioxide
 - [alk](#) = alkalinity ($\text{HCO}_3^- + 2 \times \text{CO}_3^{2-}$)

Fate of CO₂ emissions

- By 2100 cumulative emissions may reach 3000 GTC
- Type 3000 into “Transition CO₂ spike”
- Switch to 1000 year time scale
 - What happens to pCO₂?
 - What does the silicate thermostat do?
 - Look at CaCO₃ budget:
 - What happens to burial of carbonates?
 - What does it mean for carbonate burial to become negative?
 - Why is this happening?
 - **Clue:** look at Ocean CO₃²⁻ concentration
 - What happens to the temperature over time?
- Switch to 10,000 year time scale
 - What happens to ocean CO₃²⁻ & CaCO₃ budget?
 - Why?

Prospects for future:

- **Oceanic sinks:**

- A few centuries:

- Around 50% of excess CO_2 dissolves into oceans
 - Dissolution stops as oceans acidify

- A few thousand years:

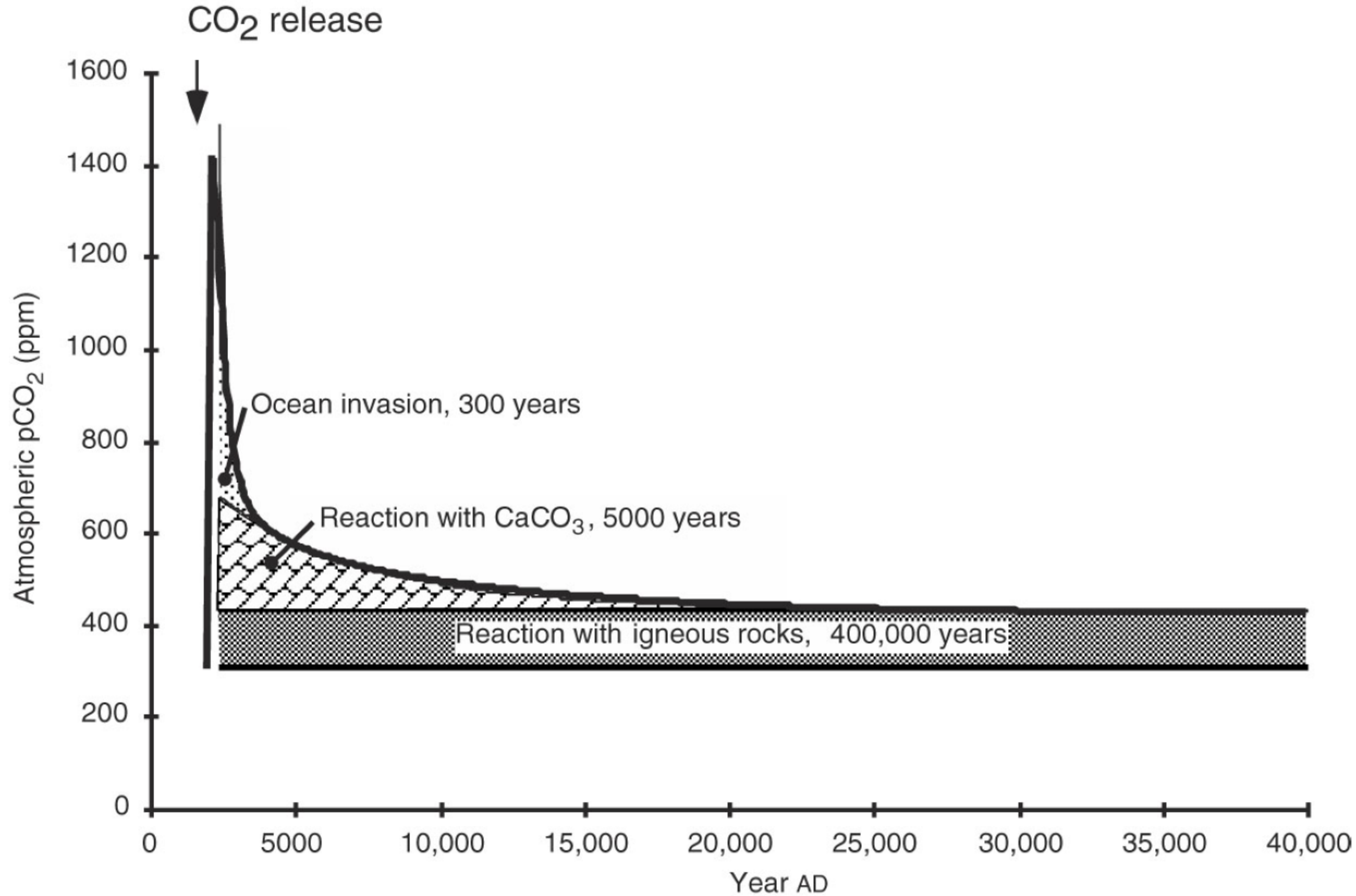
- Reactions with limestone restore pH , CO_2 solubility

- Hundreds of thousand of years

- Silicate-mineral weathering removes and buries excess CO_2 .

- **Bottom line:**

- CO_2 stays in the atmosphere many thousands of years after we stop burning fossil fuels.



CO₂ vs. Methane

- CO₂:
 - After 1000 years, around 30% of excess CO₂ remains in atmosphere
 - After 10,000 years, 13% remains
 - After 100,000 years, 6% remains
- Methane (CH₄):
 - 31 times more powerful (molecule-for-molecule) than CO₂
 - Atmospheric lifetime: 12.4 years:
 - After 25 years, 13% remains.
 - After 100 years, 0.031% remains.

Weathering as Thermostat

Weathering as Thermostat

CO_2 is balance of volcanic outgassing
and chemical weathering

- **Higher temperatures:**
 - More rain, faster chemical reactions
 - Faster weathering
 - Atmospheric CO_2 falls
- **Lower temperatures**
 - Less rain, slower chemical reactions
 - Slower weathering
 - Atmospheric CO_2 rises

Temperature of Earth

- Weathering acts as thermostat.
- Earth's temperature has been remarkably stable over time.
 - 4 billion years ago, sun was 30% dimmer...
 - But there has constantly been liquid water.
- Geologic change alters thermostat "setting":
 - Volcanic outgassing
 - Land surface (e.g., mountain ranges)
 - Vascular plants
- In the long run, silicate thermostat will fix global warming...
 - ...but it will take tens to hundreds of thousands of years.